UNCERTAINTIES AND INTERDISCIPLINARY TRANSFERS THROUGH THE END-TO-END SYSTEM (UNITES)

THE UNITES TEAM APPROACH

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Presented at Capturing Uncertainty DRI Kick-Off Meeting

Aljoya Conference Center

June 27, 2000

Environmental Uncertainty and Its Effect on Sonar Performance
UNITES Team -- An Interdisciplinary Effort, Comprised of:

OASIS Inc. [Abbot]

Harvard University [Robinson and Lermusiaux]

Woods Hole Oceanographic Inst. [Lynch, Duda and Gawarkiewicz]

Naval Postgraduate School [Chiu]

University of North Carolina [Bartek]

BBN Technologies [Cable]

Oregon State University [Miller]

Naval Research Laboratory [Gomes and Fulford]

Goals of Research

- Define and characterize variabilities and uncertainties in the components and linkages of the physical-geo-acoustical *System* relevant to the support of naval operations

- Transfer quantitatively the spatial-temporal environmental variabilities and uncertainties through the *System*, including coupled interactions, in order to determine uncertainty measures, sensitivities and feedback needed to improve operational predictions and parameters

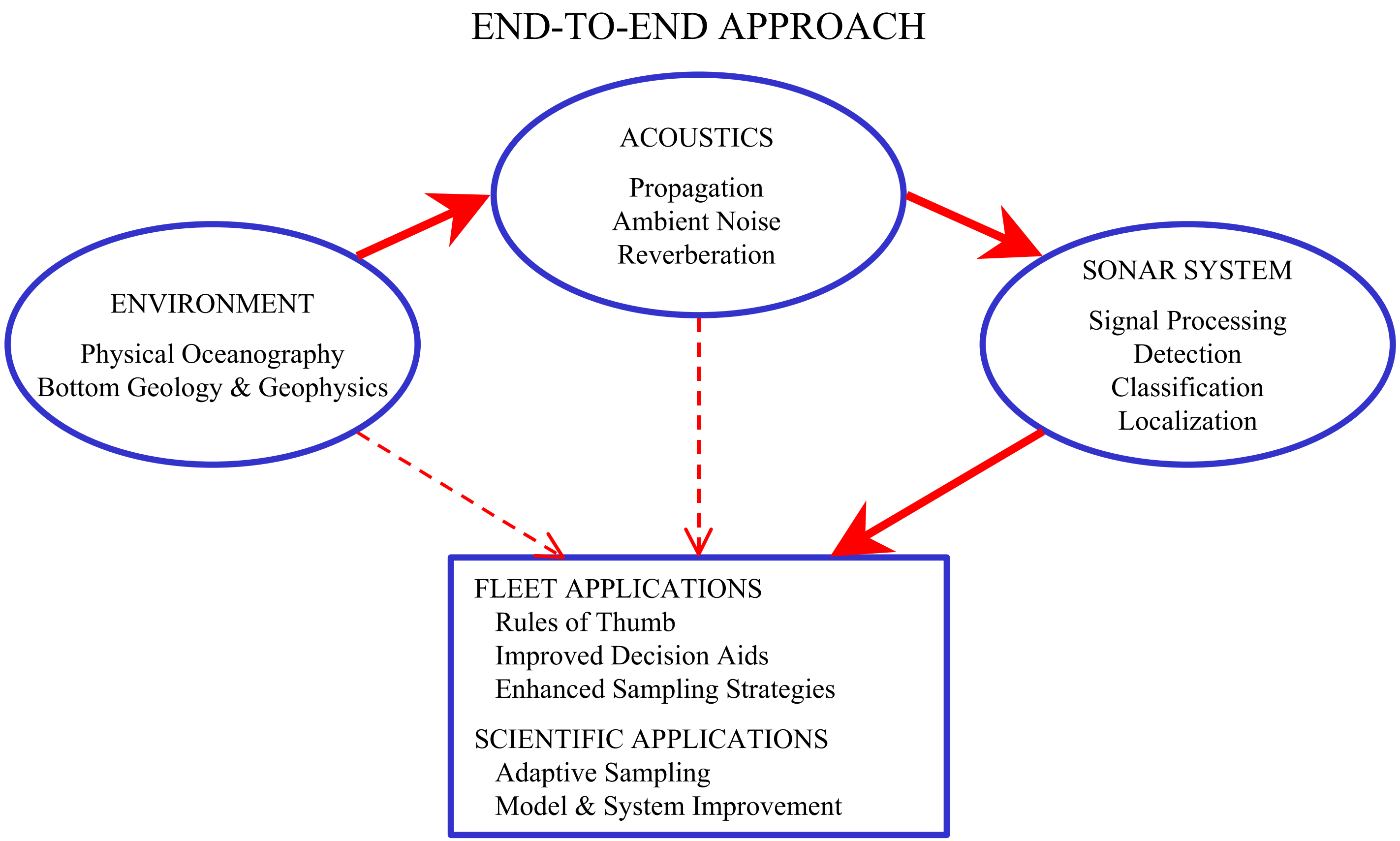
Objectives

1) Develop generic methods for efficiently and simply parameterizing, characterizing, and prioritizing *System* variabilities and uncertainties arising from regional scales and processes
2) Construct, calibrate and evaluate uncertainty and variability models, for the *System* and its components, to address forward and backward transfer of uncertainties based upon the process of end-to-end data assimilation and other methods.
3) Transfer uncertainties from the acoustic environment to the sonar and its signal processing, in order to effectively characterize and understand sonar performance and predictions

UNITES Technical Approach Overview

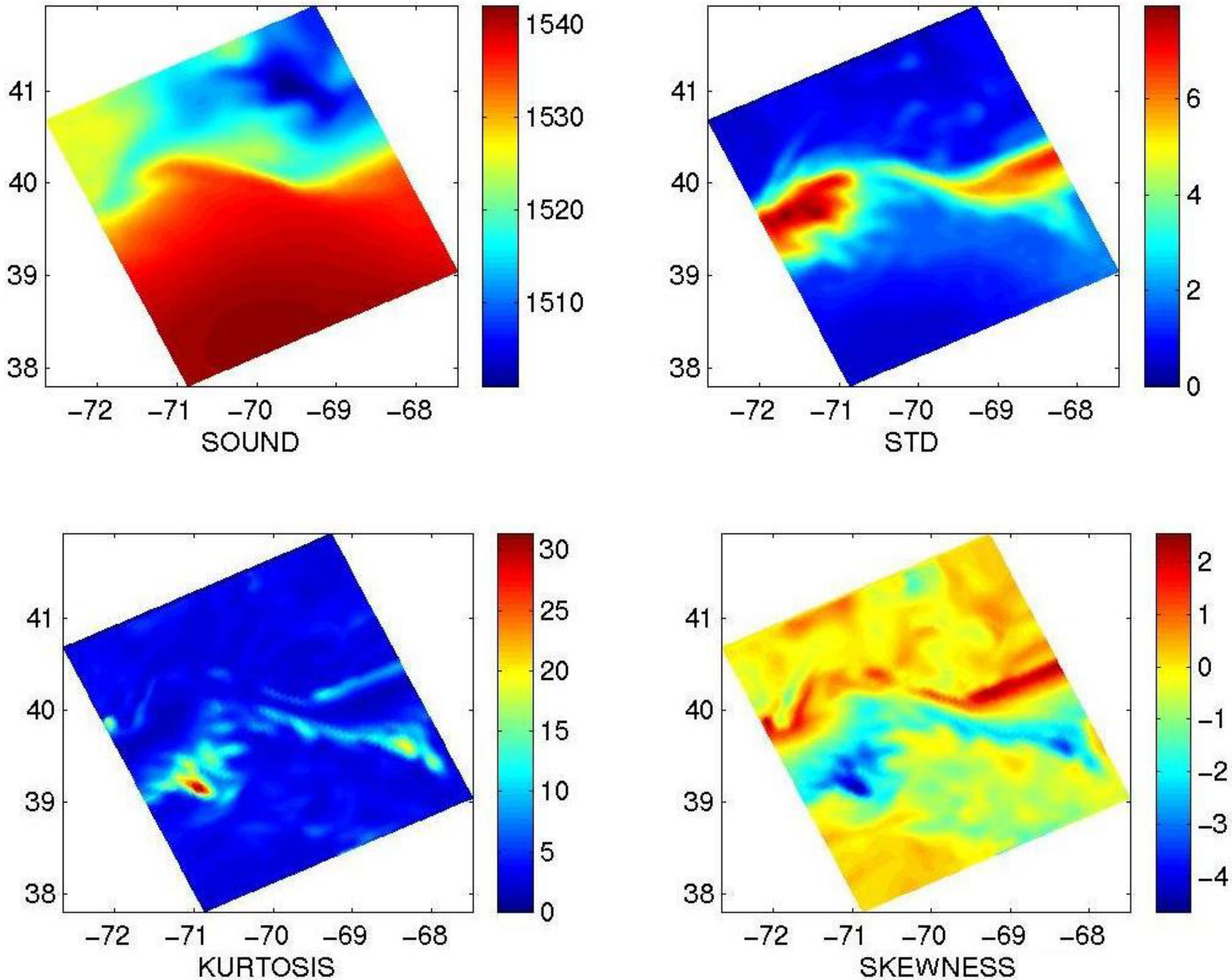
- Uncertainty Characterization
  - Ocean Physics and Bottom Environment
  - Acoustics
  - Sonar System and Fleet Application
- Sonar Systems for End-to-End Problem
  - Low Frequency Passive Towed Array
  - Low Frequency Multi-Static Active
  - Mid Frequency Surface Ship Active
- Data Sets
  - Shelfbreak PRIMER
  - ASIAEX
  - Others (Gulf of Maine, SHAREMs, Area Characterization Test)

Overview of UNITES Team End-to-End Technical Approach for Capturing and Transferring Uncertainty



Abbot et al, June 2001

Monte Carlo simulation example: transfer of ocean physical forecast uncertainty to acoustic prediction uncertainty in a shelfbreak environment.



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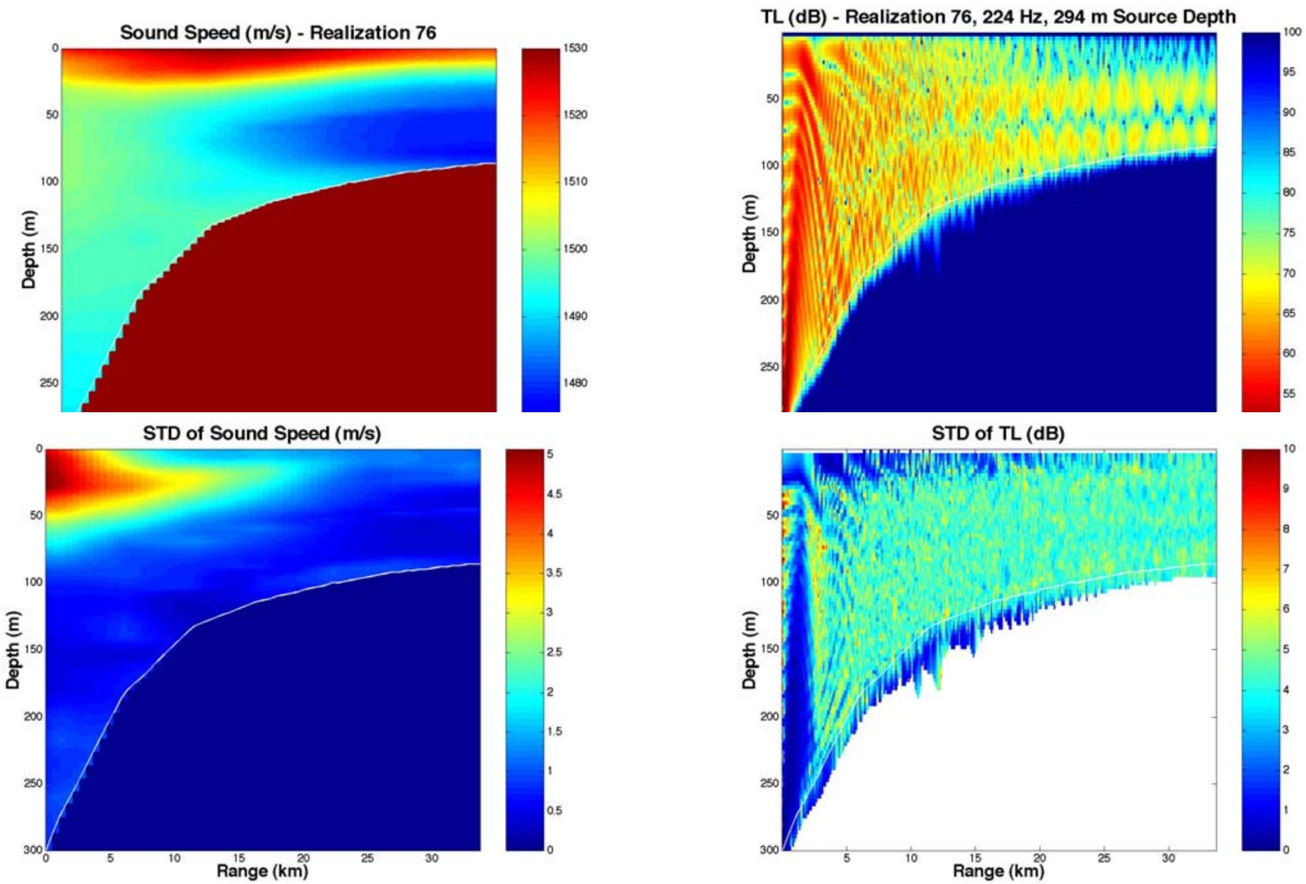
Realization of sound speed along transmission path, the corresponding TL realization, the standard deviations of the sound speed and TL realizations



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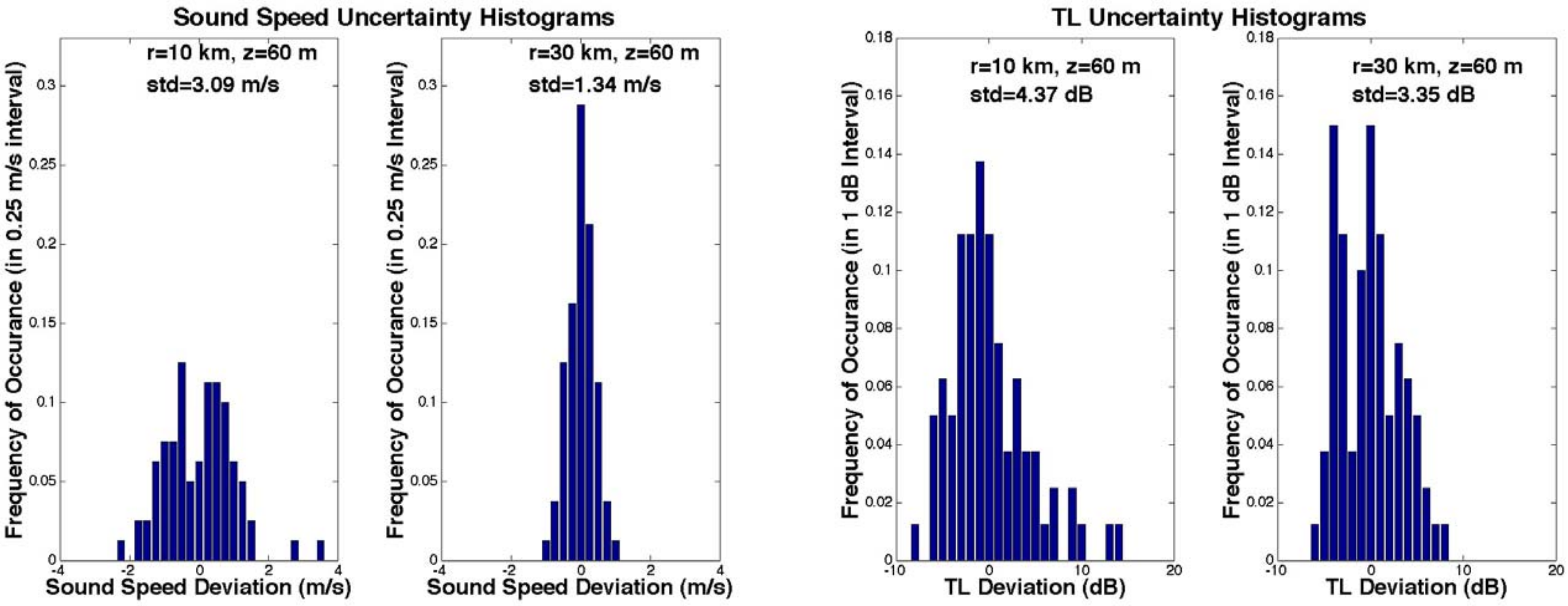
Histograms (PDF estimates) of the sound speed and TL uncertainties at two different locations (shelfbreak and shelf).



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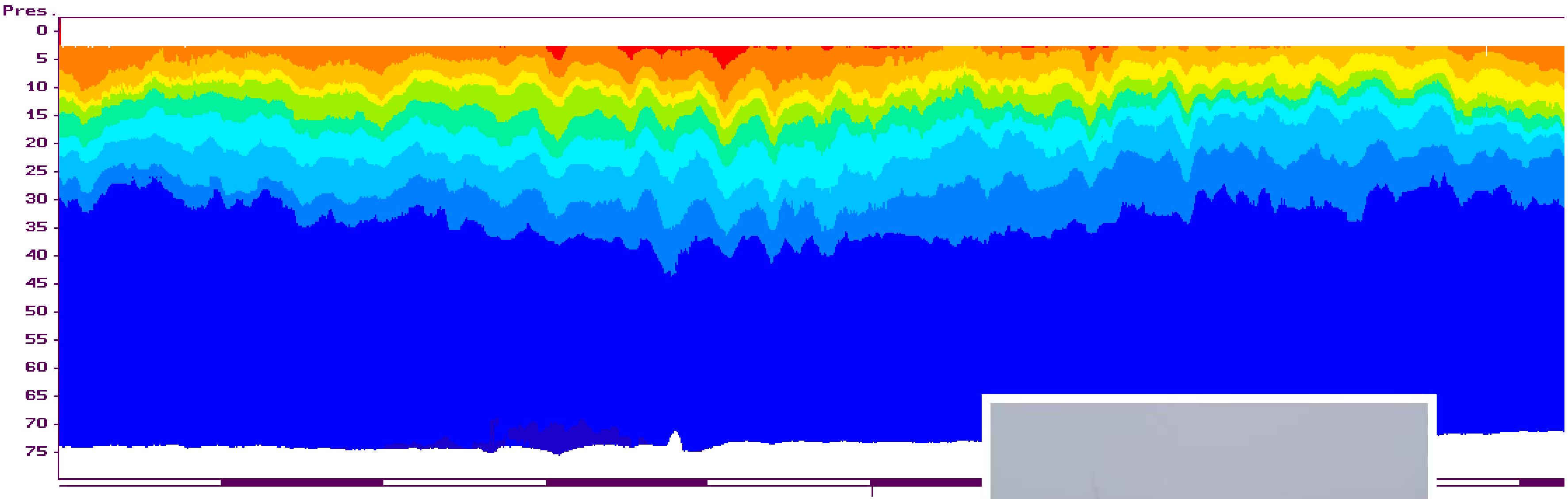
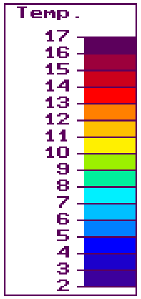
Towed CTD chain





- Bars are 1 km
- Spatial resolution 4 m horizontally and vertically
- Color steps 1 degree

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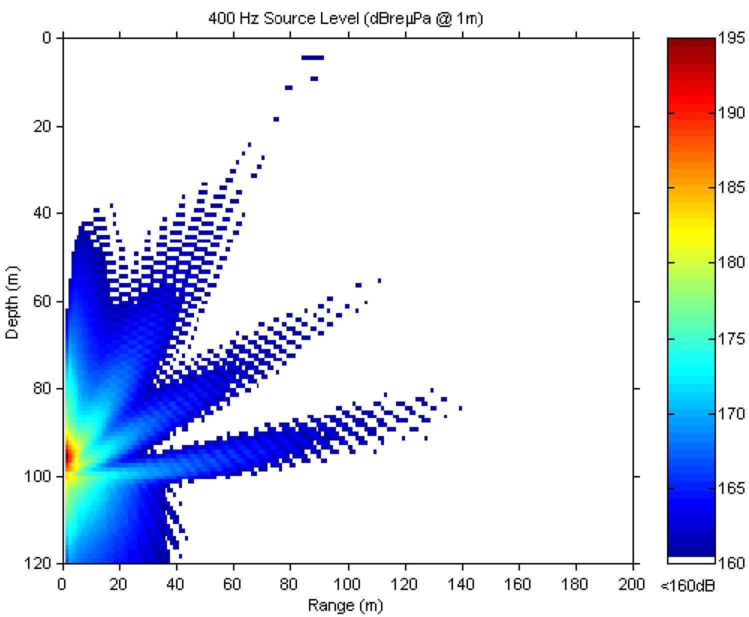
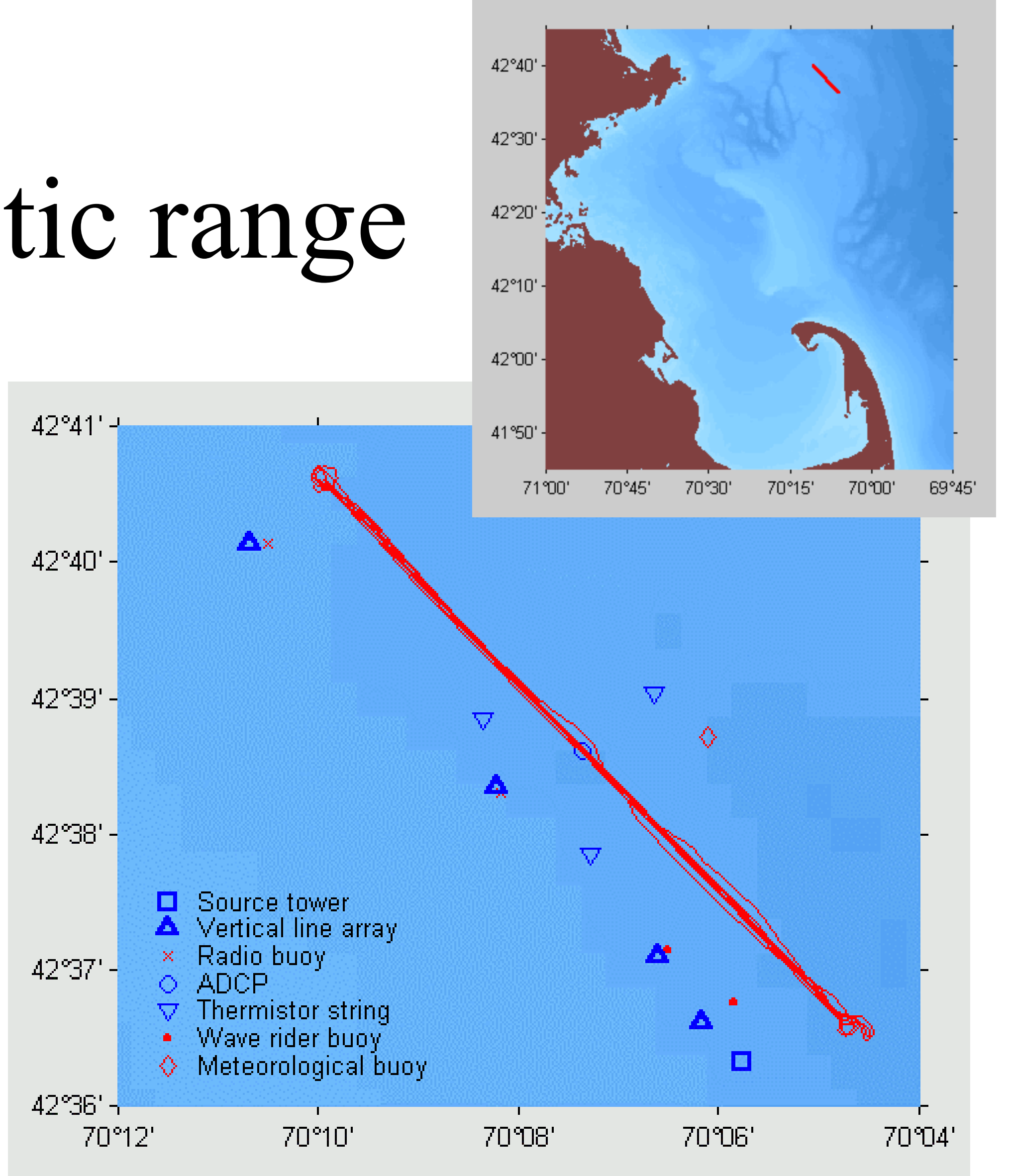
Acoustic range

100 m from the source the sound level is below 160 dB





Moorings and tow tracks

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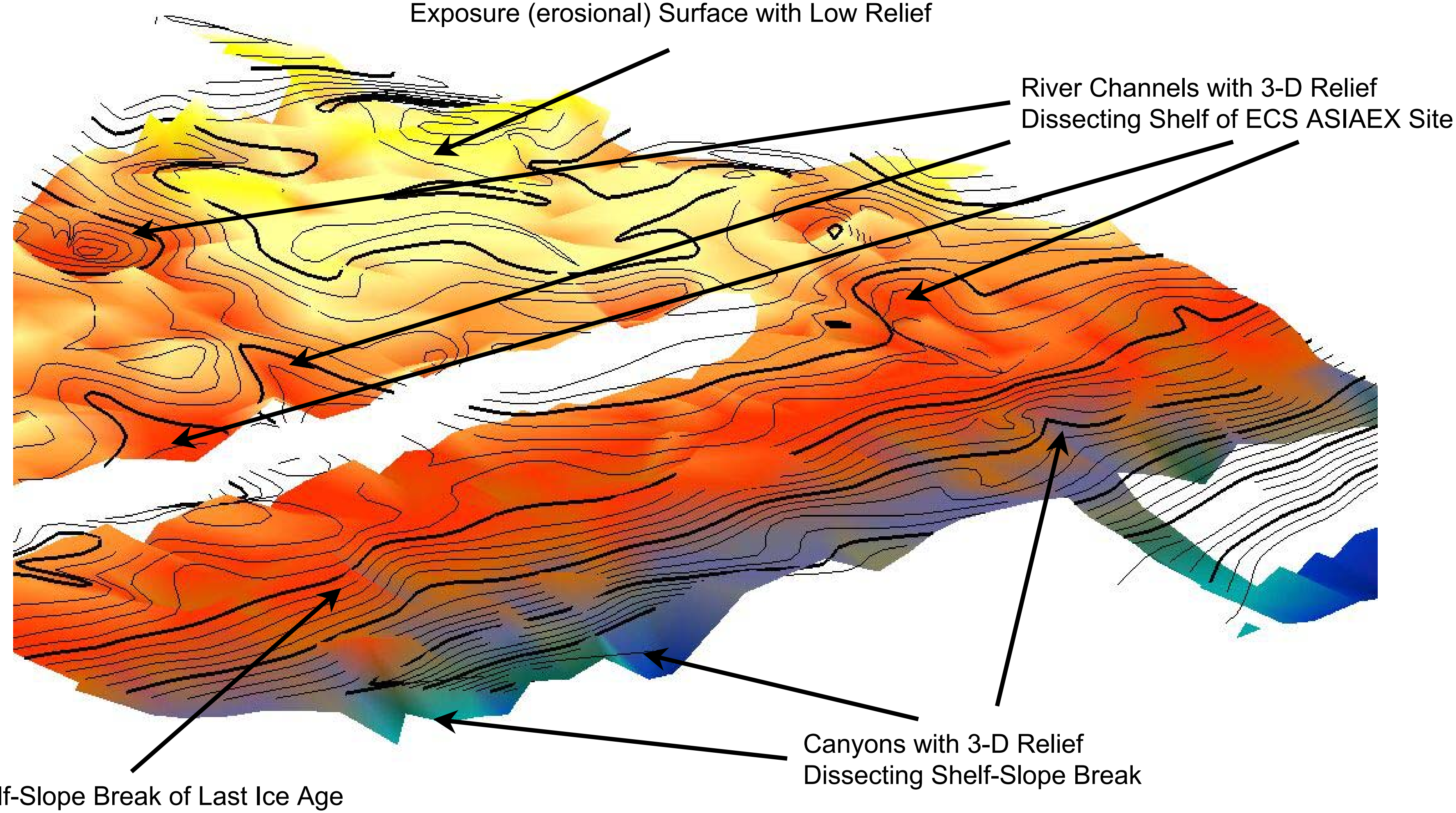
Ocean Environment Uncertainty

- Generate 4-D physical fields, parameters and their respective dominant uncertainties
  - measured environmental and acoustic data
  - ocean data assimilated in HOPS, driven by atmospheric forcings
- Study and analyze physical processes and scales - forced and internal dynamics
  - Meso- and sub-mesoscale fronts and eddies
  - Tides, internal tide, waves and solitons
- Evaluate statistics of soundspeed fields and compare with models
- Improve end-to-end data assimilation and adaptive sampling
- Conduct theoretical studies of new uncertainty models
  - Moments, multiscale decompositions, filtering and smoothing
  - Stochastic calculus, Bayesian and maximum entropy, fuzzy theory

3-D View of Sequence Boundary



View is from off of the shelf
Looking Northeast

Contour Interval = 0.002 seconds

5/25/01
Lou Bartek
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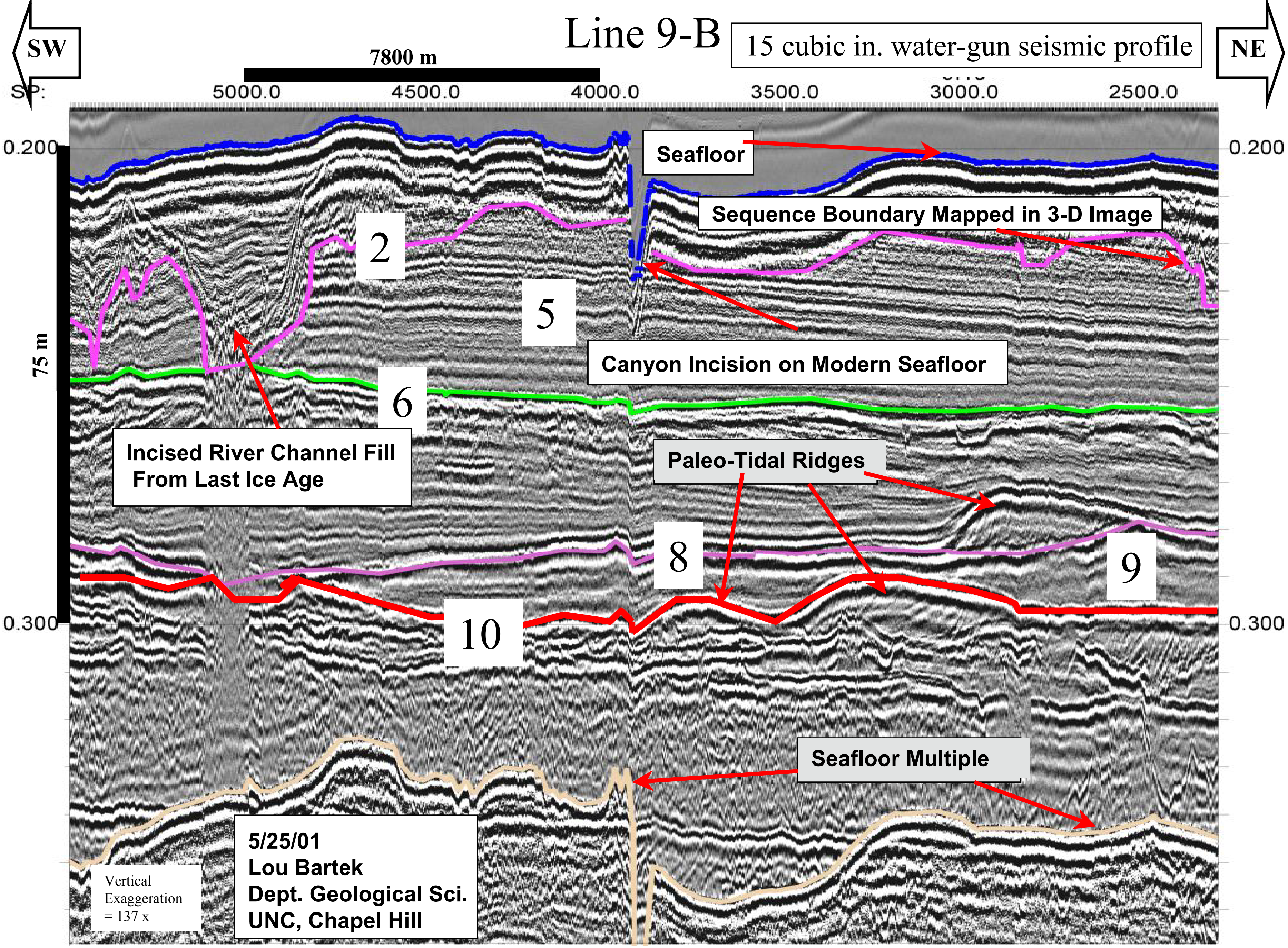

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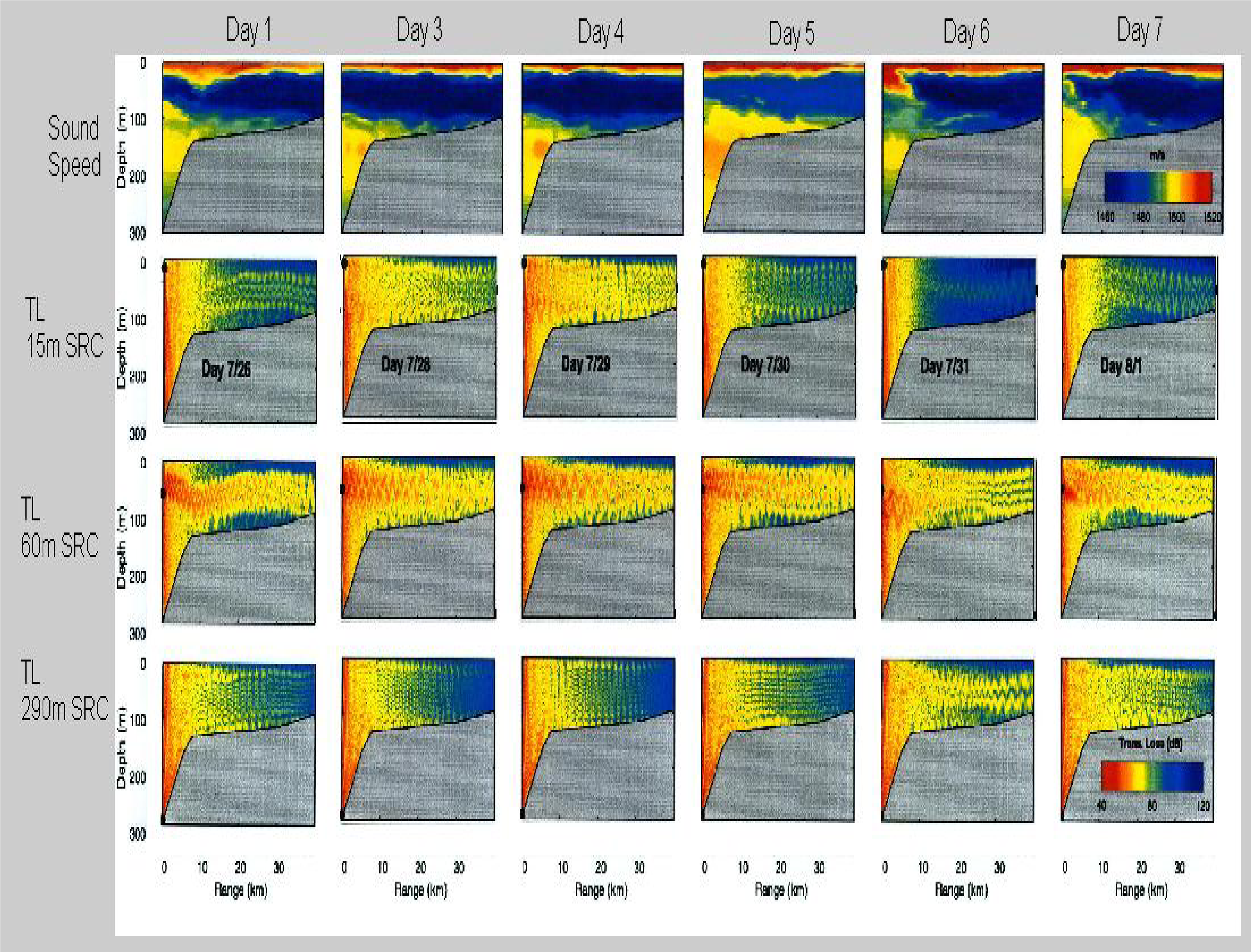
Bottom Geology Uncertainty -- Characterizing the Spatial Variability in the Bottom and Sub-Bottom

- Lateral and vertical distribution of bottom attributes (attenuation, reflectivity, velocity and density)
- Stochastic models of spatial variability of bottom attributes associated with various sets of environmental conditions
- Spatial Variability of measurable geologic quantities (grain size profiles, chemistry, and medium scale fabric) quantified by spatial statistical methods
- Optimal (minimal acoustic uncertainty) sampling locations



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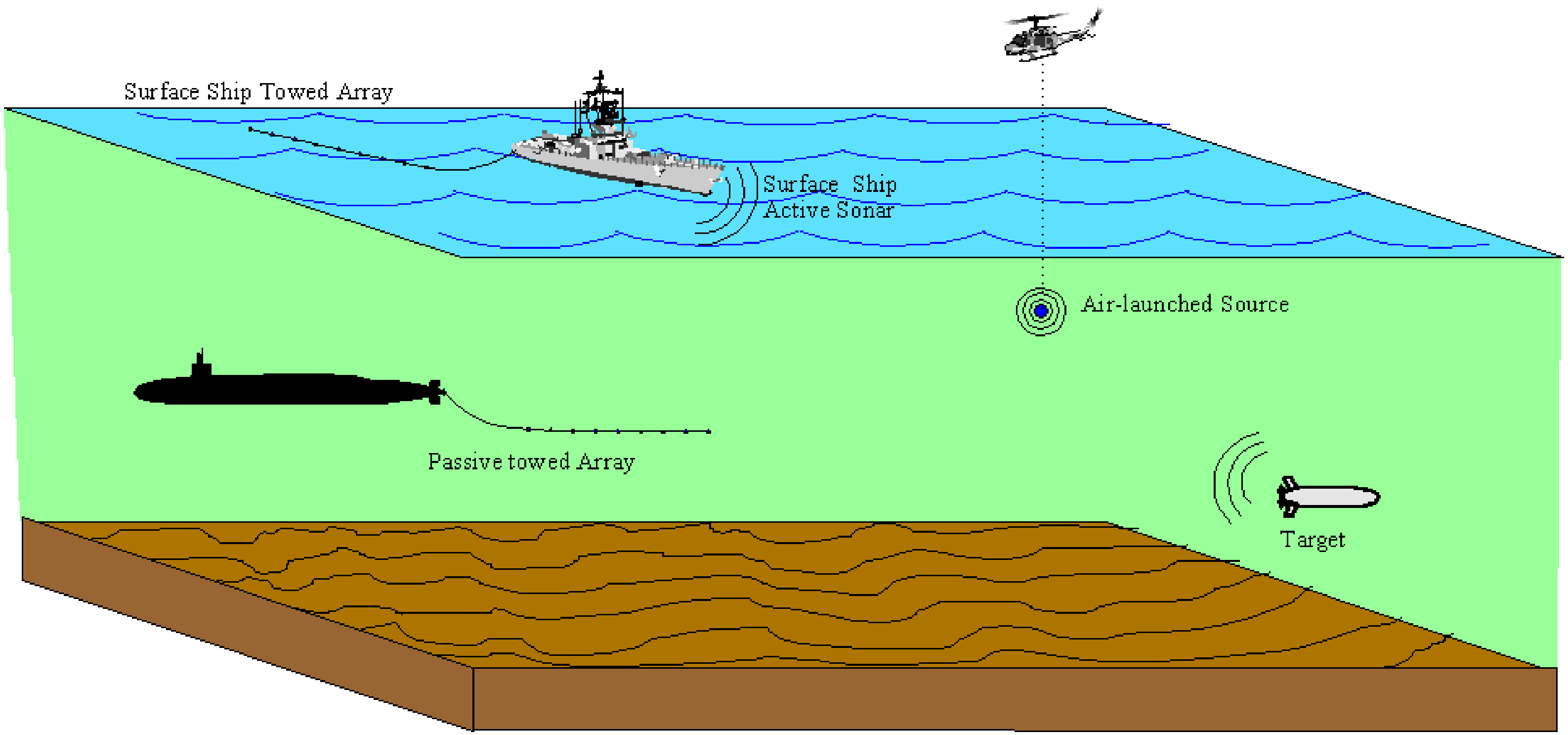
Acoustics Uncertainty

- Littoral acoustic field uncertainty characterization and transfer
  - Estimate PDFs of acoustic variables (TL, amplitude, phase, time, wavenumber, etc.) uncertainties and signal-to-interference ratios
  - Investigate the dependency of acoustic uncertainty statistics on sensor and target locations and signal parameters
- Acoustic field baseline and uncertainty forecast
  - develop data assimilation algorithm to simultaneously track (i.e. forecast) the dominant error/uncertainty structures in both the ocean and acoustic variables
- Effects of physical processes (e.g. meso-scale fronts, internal waves, etc) on acoustics and sonar performance
- Acoustic interference (reverberation and ambient noise) and impact on sonar system performance

Sonar systems to be evaluated for UNITES Team end-to-end problem



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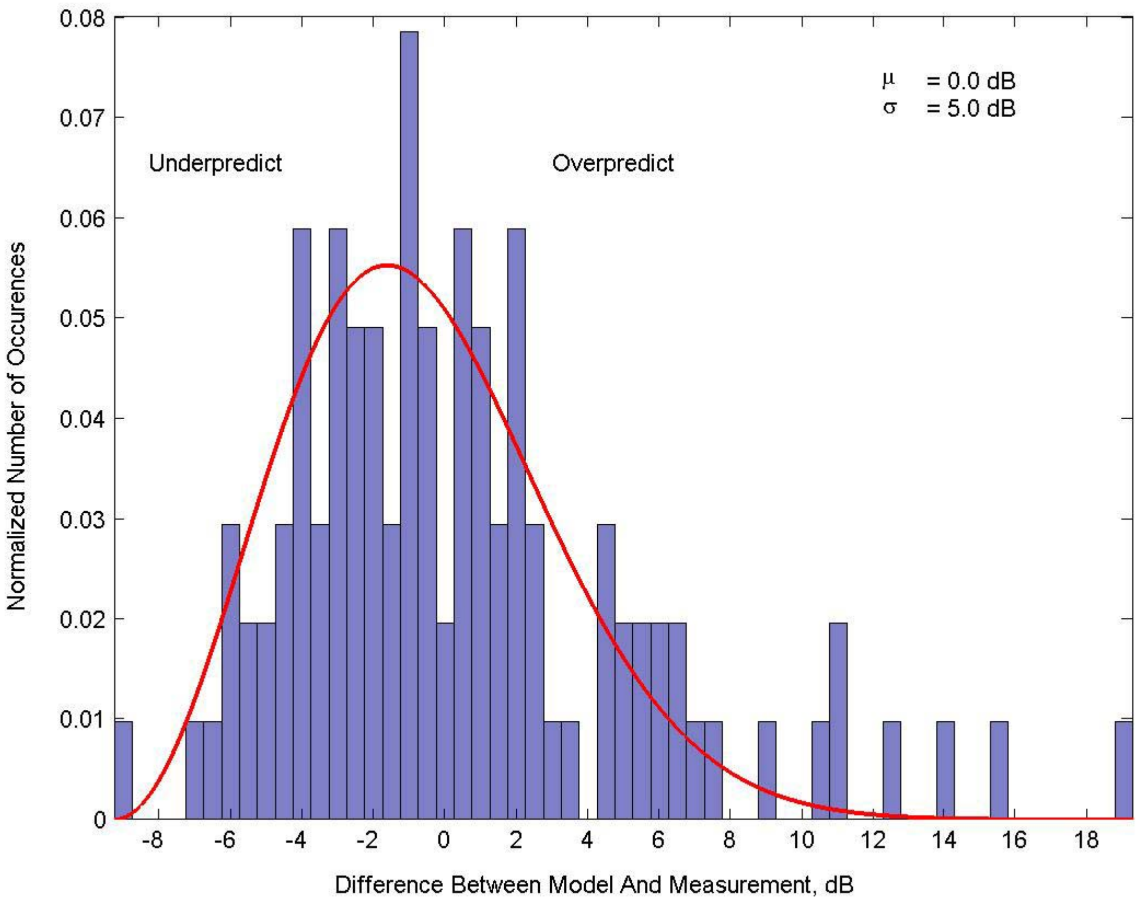
Histogram of Difference Between Model and Measured SIR, SIRE-PDF



- Represents uncertainty in our ability to model actual performance of system
- Accounts for inherent variability of environment not known by current model

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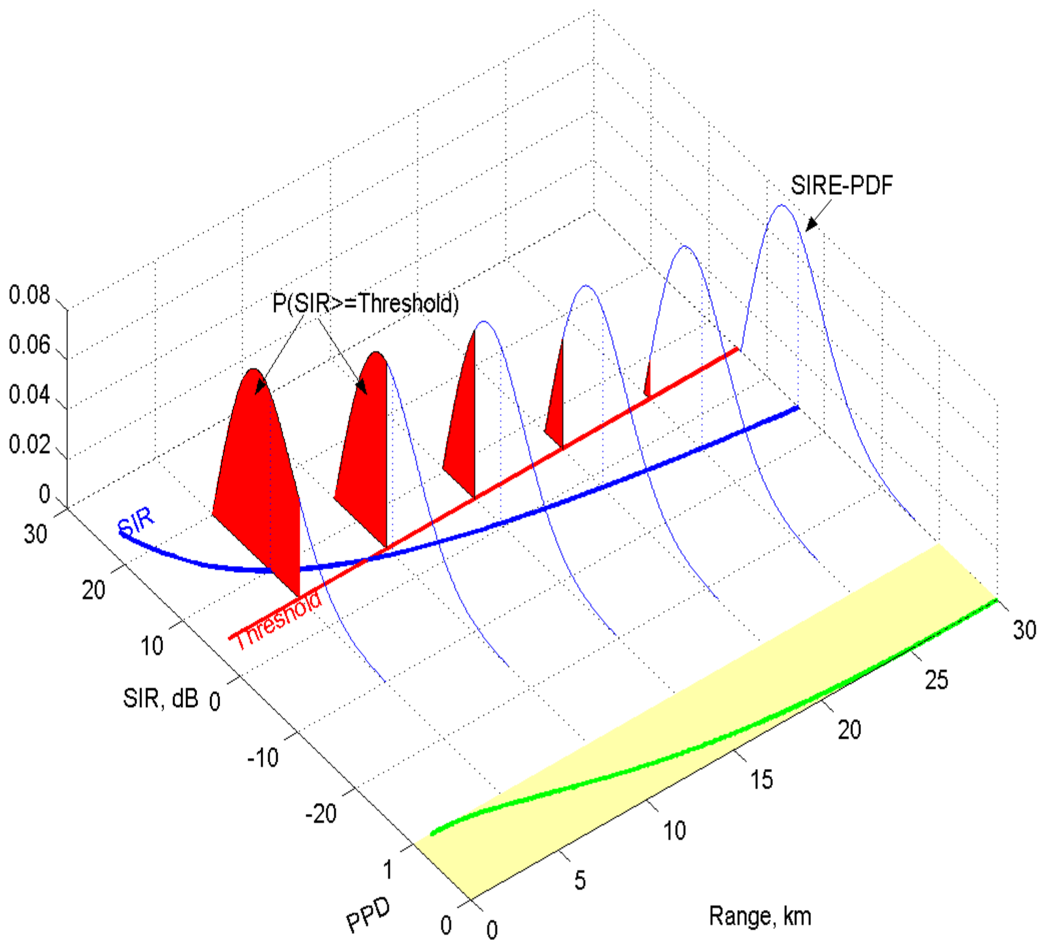
Determination of PPD (predictive probability of detection) using SIRE-PDF



•Probabilistic representation of system performance

• Used by UNITES to characterize and transfer uncertainty from environment through end-to-end problems

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Example of backward propagation of uncertainty (preliminary)

$\sigma_{TL1} \approx \sigma_{TL2} \approx 2$ dB

$\sigma_{TLB1} \approx \sigma_{TLB2} \approx 2$ dB

$\sigma_{BRev} \approx 3$ dB

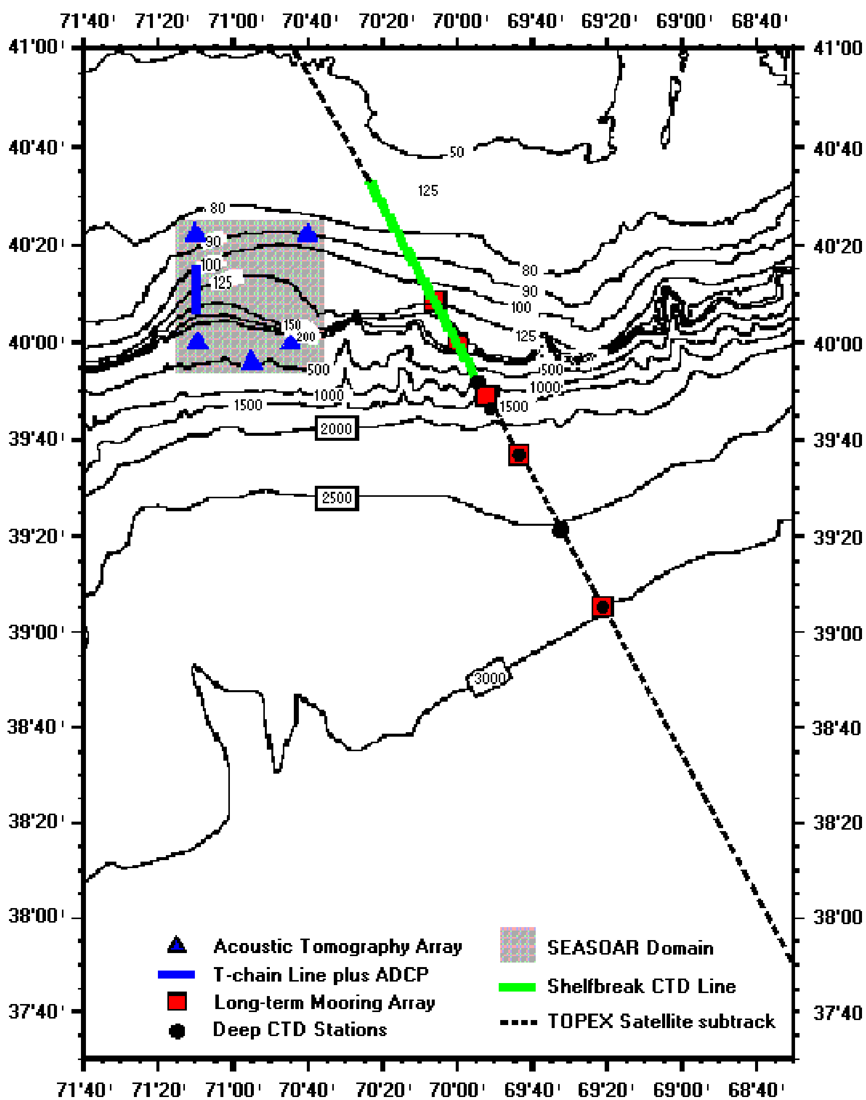
$\sigma_{S/TS} \leq 1$ dB

$\sigma_{total} \approx (2^2 + 2^2 + 2^2 + 2^2 + 3^2 + 1^2)^{1/2} \approx 5$ dB

(Statistically Independent)

Sonar Systems and Fleet Applications

- Develop Environmental SIRE-PDFs for 3 Sonars
  - Signal: target echoes
  - Interference: reverberation & ambient noise
  - Combine individual signal and interference pdfs
  - Sonar system output SIR variations relative to model
- Match physical scales (ocean and bottom) to sonar scenarios
- Develop tactical "Rules-of-Thumb" for littoral
- Design operational test to evaluate UNITES results



PRIMER IV Field Study
Feb, 1997

Shelfbreak PRIMER

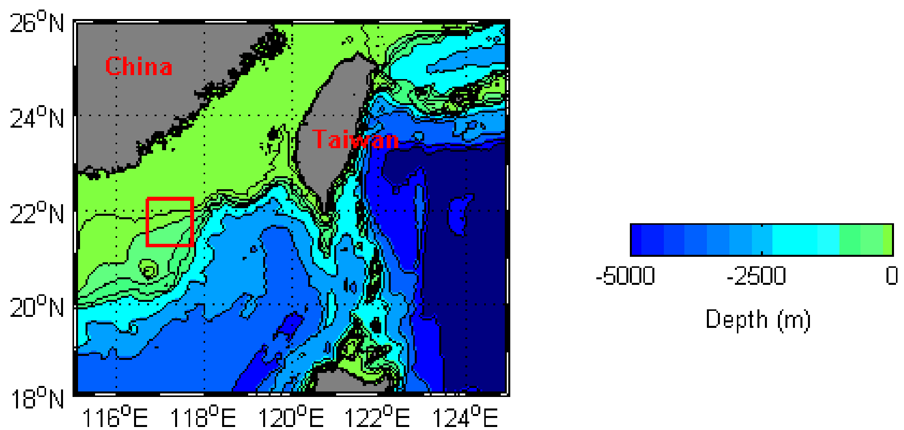
Coupled Acoustics / Physical Oceanography Data Set

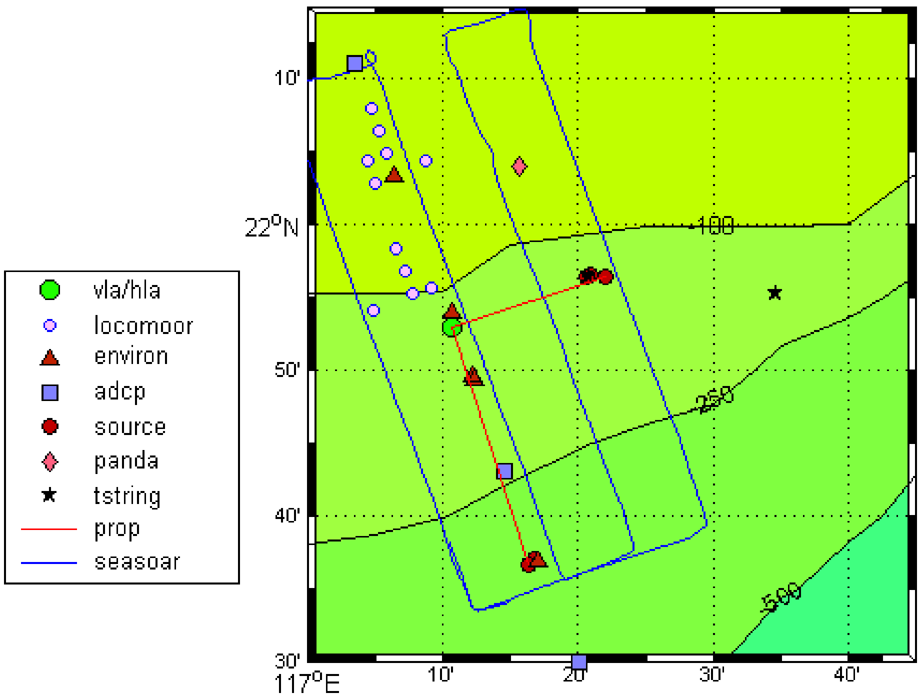
Seasonal Contrast Summer and Winter Data

Multiple Sources and Receivers

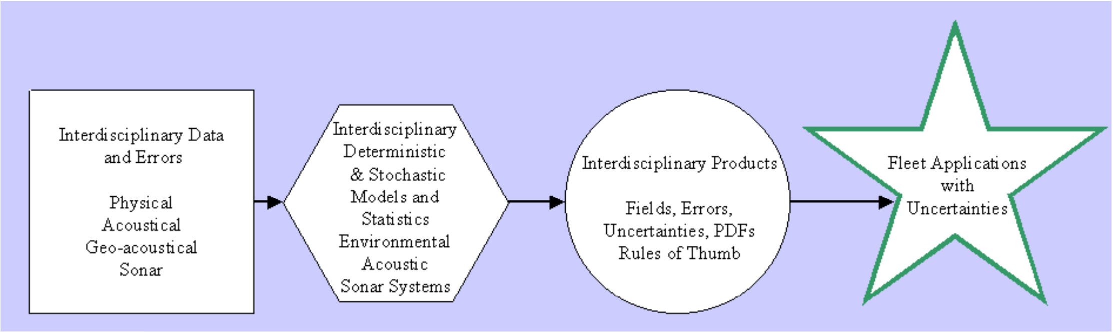
High Resolution Hydrography

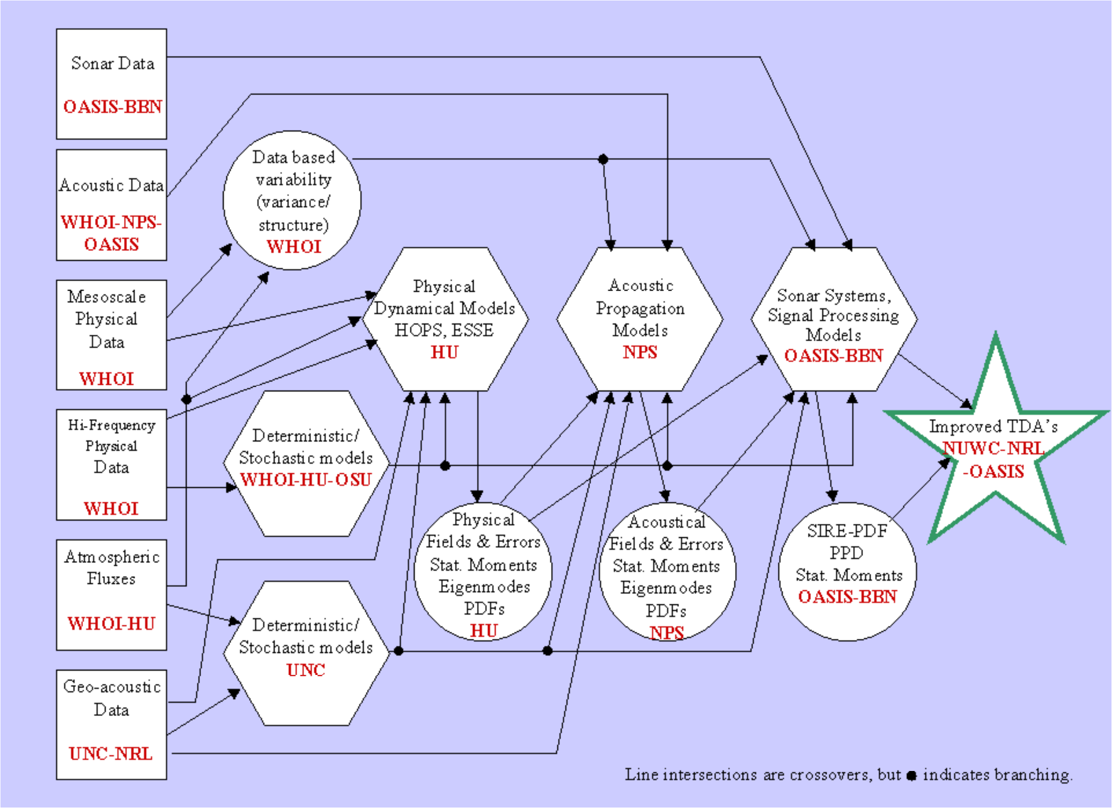
ASIAEX SCS Experiment - April-May, 2001





UNITES Example of Forward Transfer of Uncertainty





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UNITES

- Environment (ocean and bottom), acoustics and sonar performance team effort to characterize, transfer and predict uncertainty
- End-to-end transfer studies applied to 3 fleet sonar systems
- Existing data sets and generic representations as possible
- Anticipated Results
  - Improved understanding of uncertainty in environment and its impact on sonar performance, and implement advances
  - End-to-end studies (with end-to-end data assimilation)
  - Enhanced sampling strategies
  - Fleet rules-of-thumb
  - Improved tactical decision aids when operating in the littoral

Robinson and Lermusiaux/HU Effort

- Modeling and Simulating Physical Fields and High Order Uncertainties
  - Assimilate environmental data in HOPS using ESSE and OI.
  - 4D Monte-Carlo simulations
- Analyze Results and Transfer Physical Estimates to Acoustics/Signal Processing Models
  - Study influences of multiscale dynamics and data properties
  - Analyze and transfer interdisciplinary PDF's in time, space and frequency
  - Quantitative predictability limits and predictive capabilities
  - Compare Monte-Carlo simulations with simplified models
- Develop Stochastic Error Models for Unresolved Processes, Forcing and Boundary Condition Errors, and Environmental Noise
  - Improvement and validation of HOPS stochastic models:
  - Calibration and evaluation based on WHOI, NPS and UNC studies

Robinson and Lermusiaux/HU Effort

- Couple HOPS and ESSE Codes with Predictive Acoustic (NPS-Chiu) Model
- Applied Math for Characterizing, Capturing and Reducing Uncertainty for Scientific and Naval Purposes, and Implement Advances
  - Investigate idealized end-to-end uncertainty problems:
    - deterministic/stochastic calculus, nonlinear dynamical techniques
    - multiscale decompositions, filtering and smoothing
    - moments, Bayesian and maximum entropy methods, fuzzy information theories
- End-to-End Data Assimilation:extend OI/ESSE to Coupled Physical-Geo-Acoustical Assimilation
  - inclusion of geo-acoustical state variables
  - extend multiscale error initialization/forecast
- Develop Adaptive Sampling Schemes for the Acquisition of Optimal Combined Physical, Geological, Acoustical and Sonar Data Sets
- Coordinate, Provide Overview and Guide End-to-End System Research

Lynch/WHOI Effort

- PRIMER/ASIAEX analyses
  - Examine the variability in the acoustic field (various relevant quantities)
  - Compare variability with predictions based on the “best” environmental data available.
- Develop “rules-of-thumb” for predicting coastal variability
  - Along lines of Dyer’s “5.6 dB” rule for intensity.
  - Use Kravtsov’s “Acoustic Predictability” theory as basis, along with physical parameter inputs from other Uncertainty DRI P.I.’s.
- Internal wave physics and sound scattering (w/Tim Duda)
  - Quantify variations seen in non-linear internal wave field, and how such variations affect acoustic scattering.
  - Determine why SAR images of solitons don’t display amount of waves subsurface measurements do, and how the two views can be related.
- Critical transitions from ducting to non-ducting behavior.
  - Abbot and Gawarkiewicz collaboration on this issue.

Duda/WHOI Effort

- Internal Wave Effects on Acoustics
  - Importance relative to bottom knowledge (type, bathy)
  - Temporal coherence times; Spatial coherence length
  - Modal mixing (signal attenuation, dispersion)
- Quantifying Regional Internal Wavefields
  - Periodicity, directionality
  - Amplitude, fortnightly modulation
  - Winter/Summer modulation (stratification)
  - Wave types: Appropriate nonlinear equation
- Factors Controlling Internal Wave Variability/Climate :
  - Subtidal Current Field
  - Stratification and Water Masses

    …These effect both wave formation and propagation
- Motivating factors for wave/current study, in addition to acoustics:
  - Wave and current effects on equipment
  - Station keeping issues
  - Sediment flux, visibility

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Gawarkiewicz/WHOI Effort: Mesoscale Oceanography

- Continue uncertainty analyses of PRIMER data set, with emphasis on Winter data
- Compare statistics of soundspeed fields from short duration, high resolution data from PRIMER with climatological results and selected mooring arrays
- Provide data for comparison with statistics obtained from numerical model runs from Harvard OPS

Chiu/NPS Effort

Task 1: Acoustic Field Uncertainty Characterization and Transfer

- Estimate PDFs of uncertainties in the predicted acoustic variables (TL, amplitude, phase, time, wavenumber, etc.) and signal-to-interference ratios using Monte Carlo simulation techniques.
  - Use climatological data or a single profile or a forecast and first-order bottom models to define the acoustic baselines from which uncertainties are realized.
  - Acoustic calculations will be based on observed oceanographic data time series (i.e., empirical models) and HOPS ocean realizations, depending on the space and time scales of the variability, and also based on the UNC geo-acoustical parameter realizations.
  - Validate computed uncertainty statistics with acoustic data time series where possible.
- Investigate the dependency of acoustic uncertainty statistics on sensor and target locations and signal parameters, and the linkage of the acoustic uncertainty statistics to environmental uncertainty statistics.
- Supply PDF estimates to other members of UNITES in support of the end-to-end effort.
- Investigation begins with Shelfbreak PRIMER data, and will expand to include ASIAEX data in the final year.

Chiu/NPS Effort

Task 2: Acoustic Field Baseline and Uncertainty Forecast

- Joint work with Lermusiaux to develop a data assimilation algorithm to simultaneously track (i.e. forecast) the dominant error/uncertainty structures in both the ocean and acoustic variables, while improving the baselines.
- Approach uses error subspace methods and treats acoustic variables as additional state variables in a coupled ocean and acoustics forecast model.
- Test algorithm in computer simulation experiments in the initial years.
- Assess algorithm using Shelfbreak PRIMER data in later years.

Bartek/UNC Effort: Bottom Geology Uncertainty

- Objective: Quantify statistically significant trends in vertical and lateral variability in bottom attributes (attenuation, reflectivity, velocity, density and proxies thereof) on continental environments

- Background: Research on the nature of the continental margin geologic architecture that evolves in response to change in sea level, variation in sediment supply and hydrodynamic regime on the margin. Past effort focused on two “extreme end-members” (GOM , ECS & YS)

Bartek/UNC Effort: Bottom Geology Uncertainty

- Past Research Hypothesis: large difference in environmental boundary conditions between end member systems produces large and predictable differences in the distribution of attributes in the margins

- Scope of Present Work:
  – Identify nature of statistically significant trends in the lateral and vertical distribution of attributes
  – Develop stochastic models of spatial variability in distribution of attributes associated with various sets of environmental conditions

Miller/OSU Effort: Stochastic Analysis of the End-to-End System

- Approach
  - Characterize uncertainty in the environment by models which will yield parameterized pdf’s
  - Estimate evolution of pdf’s with Monte-Carlo experiments with models of the end-to-end system
  - Begin with a probabilistic approach based on the theory of stochastic differential equations
  - Consider other approaches to uncertainty such as fuzzy logic
- Tasks
  - Define working models of the environment through end-to-end system, and their associated random effect
  - Perform Monte-Carlo experiments with a predictive model of the end-to-end system and determine sensitivities of the sensor output to environmental and system uncertainties

Abbot/OASIS Effort

- Leadership for End-to-End Problem
  - Administer, coordinate and facilitate efforts of UNITES Team

- Determine SIRE-PDFs and PPDs for 3 sonar systems of interest:
  - passive, low frequency towed array
  - multi-static active low frequency
  - mid-frequency surface ship
  - when operating in:
    - Shelf-Break Primer Environment (yr. 1)
    - China Sea Environment (yrs. 2 and 3)
  - Forward and Backward Propagation of SIRE-PDFs
- Develop Tactical Rules-of-Thumb, including briefs to fleet personnel
- Design operation test to validate UNITES results (latter years)

Cable/BBN UNITES Component: End-to-End Characterization of LF Active Sonar Uncertainty

- Objective: Obtain SIRE-PDFs from modeled/measured values for LF active sonars
  - Intrinsic environmental variations
  - Measurement uncertainty
  - System-induced variability
- Approach: Conduct data-based analyses of sonar system output SIR variations about modeled values.
  - Interference: reverberation & ambient noise
  - Signal: target echoes
  - Combine separately characterized interference & signal pdfs with modeled/predicted values
- Analyses guided theory based on problem physics
- ACT I, II, III (yr. 1); ASIAEX (yrs. 2 and 3) SHAREM (various)

Gomes and Fulford/NRL Effort: Elements of Geoacoustic Uncertainty Quantification

- Three primary objectives to be considered:
  - Spatial Variability of Sampled Area
  - Sampling methods (grab, chirp, core, 3.5 echo, inversion)
  - Acoustic significance of variability in generating uncertainty in performance prediction
- Spatial Variability of measurable geologic quantities (grain size profiles, chemistry, and medium scale fabric) quantified by spatial statistical methods
- Est. geoacoustic environ. by acoustic inversion, at multiple locations
- Compare with geologic parameters to predict geoacoustic environment
- Use inversions in forward acoustic propagation at each location other than the site for which the inversion was made to estimate the variance in the acoustic performance.
- Use correlation between acoustic performance and geologic properties to infer optimal (minimal acoustic uncertainty) sampling locations.